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Potential Use of Nitrogen Reflectance Index to estimate Plant Parameters and Yield of Maize

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Estimating the spatial variability of various plant parameters during the growing season can assist in timely correction of stress conditions within a field. This research illustrates that the nitrogen reflectance index (NRI) developed to estimate plant nitrogen status can be used to estimate plant parameters and yield potential. The study was conducted on two experimental maize sites. Selected maize hybrids were 'Pioneer 3790', which was a planophile canopy architecture and 'NC+ 1598' with an erectophile canopy architecture. The first site consisted of six non-replicated fertiliser plots. Data from these plots were used to develop the relationships between reflectance data and the plant parameters. The second site contained four plots with various nitrogen (N) and water treatments on which the developed relationships were verified. Leaf area, biomass, and plant reflectance data were collected almost weekly from both sites during the 1996 growing season. Measured and estimated yield, leaf area index (LAI) and dry matter were mapped in ArcVIEW geographical information system. Results showed that the NRI was a comparable estimator of potential yield to the normalised difference vegetation index or to the modified soil adjusted vegetation index. For the LAI and biomass, all vegetation indices produced similar coefficients of determination. Results showed that the NRI could be used to estimate the within-field variation of yield potential and plant parameters.

1. Introduction

Plant development varies within a field due to the spatial variability of soil characteristics and agricultural inputs. Determination of the variations in plant development can be valuable, especially where development is affected by a stress condition that can be corrected. Plant parameters such as leaf area index (LAI) and dry matter production can be used as indicators of plant performance. These parameters play crucial roles in plant growth. Wiegand *et al.* (1979) noted that the LAI could be used to characterise crops for interception and penetration of photosynthetically active radiation (PAR) that is needed for photosynthesis or the simulation of plant growth by crop growth models. LAI was also used to partition energy between soil water evaporation and transpiration from plants (Rosenthal *et al.*, 1977). These parameters can be determined by ground measurements that are time consuming, laborious, and require many samples to obtain information about the spatial distribution.

Remote sensing techniques have been used to estimate various plant parameters (Wiegand *et al.*, 1979; Price & Bausch, 1995). They provide quantitative information about agricultural crops instantaneously and, above all, non-destructively (Clevers, 1988). Many vegetation indices have been developed for estimating plant parameters. These vegetation indices may use simple ratios of any two single wavelengths or may include more complicated wavelength combinations. Colwell (1973) used the near-infrared/red (λ_{NIR}/λ_R) ratio for estimating biomass and concluded that the ratio was somewhat effective in normalising the effect of reflectance variation in soil background. Deering (1978) proposed that the vegetation index originally discussed by Rouse *et al.* (1973) be used to estimate biomass and called it the normalised difference vegetation index (NDVI). The formula is given as

$$I_{NDV} = \frac{(\lambda_{NIR} - \lambda_R)}{(\lambda_{NIR} + \lambda_R)} \tag{1}$$

where: I_{NDV} is the normalised difference vegetation index; and λ_{NIR} and λ_R are near-infrared spectral band and red spectral band, respectively.

Wagner (1994) related the NDVI to the LAI using satellite imagery. Yang and Anderson (1996) found that plant height, biomass, and yield were correlated with the NDVI as well as the red spectral band and the green spectral band. Taylor *et al.* (1997) mapped within-field variation of yield potential by high-resolution remote sensing using airborne digital photographic (ADP) imagery. They found that the yield forecast, calculated from the number of ears per unit area and the number of viable grains per ear, was linearly related to the NDVI calculated from the ADP imagery.

The normalised difference vegetation index has been adjusted for the soil background since the NDVI is affected by soil brightness (Huete *et al.*, 1985). The resulting index was a soil adjusted vegetation index (SAVI) denoted by I_{SAV} (Huete, 1988). In SAVI, a constant L was introduced correcting for the plant cover; it is usually taken to be 0·5:

$$I_{SAV} = \frac{(\lambda_{NIR} - \lambda_R)}{(\lambda_{NIR} + \lambda_R + L)}(1 + L) \tag{2}$$

Qi *et al.* (1994) developed a modified version of SAVI (MSAVI) which replaced the constant L; it is expressed as

$$I_{MSAV} = \frac{2 \times \lambda_{NIR} + 1 - \sqrt{(2 \times \lambda_{NIR} + 1)^2 - 8 \times (\lambda_{NIR} - \lambda_R)}}{2} \tag{3}$$

where I_{MSAV} is the modified soil adjusted vegetation index.

The indices mentioned so far were developed for the whole growing season. Therefore, they may over- or underestimate the plant parameter at a specific growth stage. For precision farming, growth-stage-based indices may be needed to avoid the smoothing that may occur when whole season equations are used for a specific stage. Bausch and Duke (1996) proposed a vegetation index called the nitrogen reflectance index (NRI). The index requires a relationship for each growth stage since it was normalised to a reference representing an area where there is no N stress. The formula was given as

$$I_{NR} = \frac{(\lambda_{NIR}/\lambda_G)_{area\ of\ interest}}{(\lambda_{NIR}/\lambda_G)_{reference}} \tag{4}$$

where: I_{NR} is the nitrogen reflectance index; and λ_{NIR} and λ_G are near-infrared and green spectral bands, respectively.

They correlated this index with the nitrogen sufficiency index (NSI) described by Peterson *et al.* (1993), and the total nitrogen percentage in the plant. The formula for NSI was given as

$$I_{NS} = \frac{(C_{av})_{area\ of\ interest}}{(C_{av})_{reference}} \times 100 \tag{5}$$

where: I_{NS} is the nitrogen sufficiency index; C_{av} is the average chlorophyll meter reading; and the *reference* is an area where there is no nitrogen stress.

There was a near 1:1 relationship between the NRI and the NSI. Bausch *et al.* (1996) and Diker (1998) successfully used the NRI to estimate plant nitrogen status and illustrate the spatial variability of plant nitrogen status in the field. Diker and Bausch (1998) employed the NRI to estimate within-season soil nitrogen content, as well as a prescription nitrogen application for maize. However, the information about the performance of the NRI in estimating plant parameters such as LAI, dry matter and yield is limited. Therefore, the objective of this study was to determine the performance of the NRI, in comparison to the NDVI and the MSAVI, for estimating the LAI, dry matter and yield for two maize canopy architectures, and to use developed relationships to predict LAI, dry matter, and yield of maize grown in another experiment.

2. Procedures

2.1. *Experimental layout and treatments*

The research was conducted at the Agricultural Research, Development and Education Center, Colorado State University, Fort Collins, CO, USA during the 1996 growing season. In the first experiment (calibration), the yield response of two maize (*Zea mays L.*) varieties with different canopy architectures to six non-replicated fertiliser levels was studied. Selected maize hybrids were 'Pioneer 3790' which was a planophile canopy architecture and 'NC+ 1598' which was an erectophile canopy architecture. Plots (22 m by 22 m, east side of *Fig. 1*) were divided in half from North to South to accommodate the two maize varieties. Row spacing was 0·76 m and the row direction was north–south in both studies. Six nitrogen (N) fertiliser levels of 0, 56, 84, 112, 168 and 224 kg ha^{-1} were applied to both varieties before planting to create high variability in plant development. For this experiment, the 224 kg ha^{-1} N treatment was used as the reference area to normalise

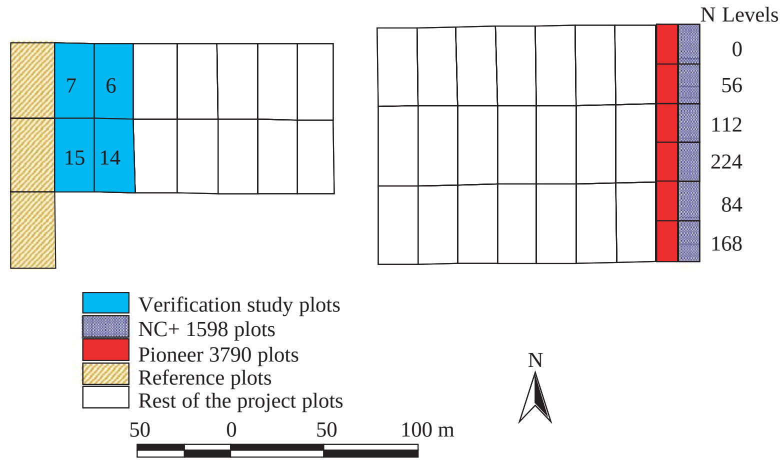

Fig. 1. Experimental layout showing fertiliser level study plots and verification study plots for two maize hybrids 'NC+ 1598' and 'Pioneer 3790'

Table 1
Phenological observations for the two maize varieties, 'Pioneer 3790' and 'NC + 1598', crop growth stages are based on Ritchie et al. (1993)

Day of year	*Growth stage*	
	Pioneer 3790	*NC+1598*
123	Planting	Planting
135	Germination	Germination
138	Emergence (VE)	VE
176	Sixth leaf (V6)	V6
193	Ninth leaf (V9)	V9
199	Twelfth leaf (V12)	V12
205	Tasseling (VT)	V14
213	Silking (R1)	Early R1
219	Early blister (R2)	R1
226	Blister (R2)	Early R2
239	Late Milk (R3)	R3

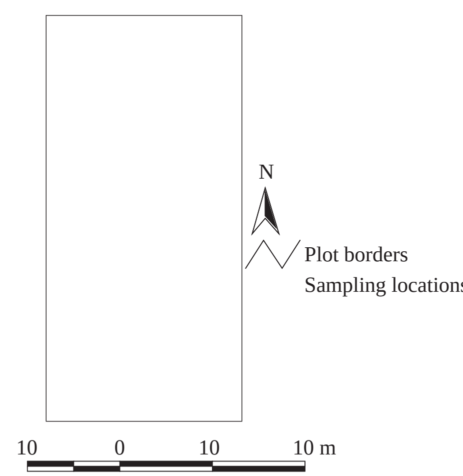

Fig. 2. Sampling locations in the verification study plots

the NRI for the various treatments. Canopy reflectance measurements and plant sampling was conducted on the same day for each maize variety in the fertiliser level study except at the R1 growth stage. At this growth stage, separate sampling was conducted for the two varieties because there was considerable difference in growth stages. Relationships between the plant (LAI, dry matter and yield) parameters and the vegetation indices (NRI, NDVI and MSAVI) were developed from this study. Although both varieties had similar maturity ratings, hybrid 'NC + 1598' developed at a slower rate than maize hybrid 'Pioneer 3790' (Table 1). This was especially evident late in the growing season.

The second experiment (verification) was conducted to verify the relationships between plant measurements and spectral indices developed from the fertiliser level study. Maize hybrid 'Pioneer 3790' (planophile canopy architecture) was planted. Four nitrogen (N) fertiliser and two irrigation water level treatments were applied to plots with plot dimensions of 22 m by 44 m. Two of the four plots were prescription fertiliser plots (plots 7 and 14), one was pre-plant fertilised (plot 6), and one was sidedress fertilised (plot 15). The difference between the two prescription N treatments was that plot 7 had 100% of evapotranspiration applied as irrigation whereas plot 14 had 150%. All other treatments in both experiments had 100% of evapotranspiration applied as irrigation water by a linear-move sprinkler system. Eight sample locations, as seen in *Fig. 2*, were established within each of the four plots for periodic plant measurement of biomass and the LAI. The three plots on the west side of *Fig. 1* had 224 kg ha^{-1} N applied before planting. This was the reference area used to normalise the NRI for the verification study plots.

2.2. *Measurements*

An Li-Cor LI-3000 portable leaf area meter was used to measure 16 plants in each plot of the fertiliser level study and three plants at each sample location in the verification study. Mean LAI was calculated based on the plant population in a given plot or sample location. At each designated growth stage, eight plants from each plot in the fertiliser level study and three plants from each sample location in the verification study were removed (severed at the soil surface). The plants were oven-dried at 55°C for at least 24 h, weighed, and dry matter yield was calculated. Grain yield was determined by hand sampling three rows 3·5 m in length within each plot in the fertiliser level study and two rows 3·5 m in length at each sample location in the verification study. Yield was corrected to 15·5% moisture content.

Maize canopy radiance and incoming irradiance were measured simultaneously with a mobile data acquisition system incorporating two Exotech 100BX four-channel radiometers. The radiometers were mounted on a boom with a height of 10 m above ground. The down-looking radiometer measured target radiance and fitted with 15° circular field of view (FOV) optics. It was pointed perpendicular to crop surface. The viewed spot on the ground had a diameter of 2·6 m. The other radiometer looked upward to measure irradiance; its FOV was 180°. Radiances were measured in the green, red and near-infrared (0·52–0·60, 0·63–0·69 and 0·76–0·90 μm, respectively) portions of the electromagnetic spectrum which are similar to the Landsat Thematic Mapper wavebands (Bausch *et al.*, 1990). Bidirectional reflectance of the target was calculated using the procedure described by Neale (1987). These measurements were made around solar noon on the same day plant measurements were taken. The NRI, NDVI, SAVI and MSAVI were calculated from reflectance data. Relationships between the vegetation indices and LAI, dry matter, and grain yield were developed for each maize variety at the V6 (sixth leaf stage), V9, V12, V15, R1 (silk stage), and the R2 (blister stage) growth stages (Ritchie *et al.*, 1993) (Table 1).

The spatial variability of the LAI, dry matter and grain yield were mapped using ArcVIEW geographic information system (GIS) (ESRI, 1996) for both measured and values predicted from vegetation indices. Inverse distance weighted (IDW) interpolation with a 16 m radius and a power of two was employed for mapping.

3. Results and discussion

Linear and non-linear relationships between the LAI and NDVI and MSAVI are given for the data collected from both hybrids between the V6 and R2 growth stages in *Figs 3* and *4*, respectively. The linear and non-linear relationships produced similar coefficients of determination r^2 values for both vegetation indices. The values of r^2 for the NDVI were 0·93 and 0·99 for the linear and non-linear relationships, respectively (*Fig. 3*). The MSAVI and LAI also related well (*Fig. 4*). The LAI values for

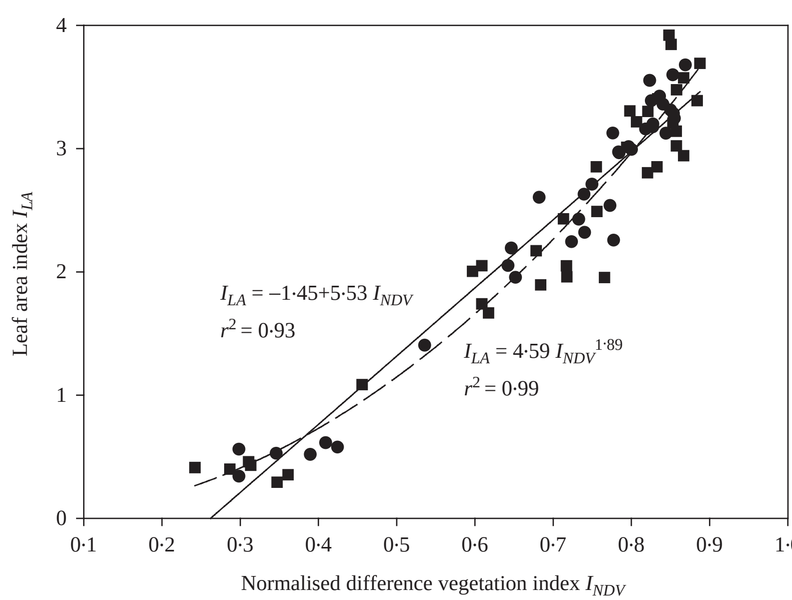

Fig. 3. Normalised difference vegetation index (NDVI) as a predictor of leaf area index (LAI) through growing season for both maize varieties in the calibration experiment: ●, planophile; ■, erectophile

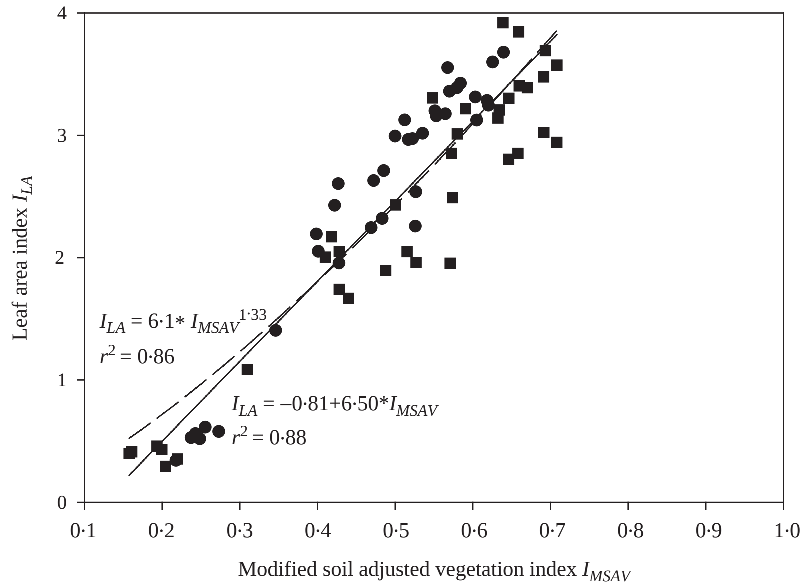

Fig. 4. Modified soil adjusted vegetation index (MSAVI) as a predictor of leaf area index (LAI) through growing season for both maize varieties in the calibration experiment: ●, planophile; ■, erectophile

the planophile maize canopy were generally higher than those for the erectophile maize canopy for the same MSAVI value. In fact, the regression line behaved as a separator between the maize canopy architectures, indicating that the MSAVI might be more affected by canopy types than the NDVI. The values of r^2 (0·88 and 0·86) for the MSAVI for the linear and non-linear relationships were similar. This indicates that the linear relationship was essentially comparable to the non-linear relationship between the NDVI and the MSAVI and LAI for the segment of the growing season investigated. The literature indicates that the non-linear relationship between the NDVI and LAI is due to saturation behaviour in the spectral wavebands at high LAI (Epiphanio & Huete, 1995). Therefore, the linear relationship between plant parameters and the vegetation indices was used for further analysis. The advantage of using linear relationship over the non-linear relationship is simplicity. A linear relationship between the parameters was also necessary for each growth-stage because the NRI is growth-stage dependent since it is normalised with a reference.

Table 2 presents the relationships between the vegetation indices and the LAI, dry matter and grain yield for the erectophile and planophile canopy types at various growth stages of maize. All vegetation indices seemed to be performing poorly at the V6 growth stage. Data indicated that the NRI and NDVI, in general, were related better with the crop growth parameters and yield, respectively, for the planophile and erectophile canopy types.

As indicated by the values of r^2, strong relationships were produced by the vegetation indices at later stages. At the R1 growth stage, all three indices produced similar values of r^2 for yield of the erectophile canopy type; however, the NRI and MSAVI correlated with the grain yield considerably better than the NDVI for the planophile canopy type. As seen in Table 3, the canopy cover was usually larger for the planophile canopy. In general, the canopy cover increased gradually until the V15/R1 growth stage and started decreasing. At the V9 growth stage, the canopy cover was 0·44 and 0·64 in the 0 and 224 kg ha^{-1} N treatments for planophile cover type, respectively. Corresponding values for erectophile-cover-type treatments were 0·37 and 0·60. This result indicates that with the same background, three indices perform similarly.

For practicality purposes, data collected at each growth stage were combined to develop a single relationship that could be used for both canopy types. Thus, data from both canopy types were used to develop relationships between the LAI and the NRI, NDVI, SAVI and the MSAVI for both maize canopy types. A relationship was developed for each growth stage since the λ_{NIR}/λ_G ratio for the area of interest is normalised by the λ_{NIR}/λ_G ratio of a reference area for calculating the NRI. Strong relationships were observed between the parameters. Table 4 compares the vegetation indices in estimating the LAI at various maize growth stages. The best relationships were produced by the NDVI and MSAVI, followed by the SAVI and NRI at the V9 growth stage. The values for r^2 were 0·87, 0·63, 0·85 and

Table 2
Values for the intercept, slope and the coefficient of determination r^2 for the relationships between the vegetation indices and the leaf area index (LAI), dry matter and grain yield for both canopy types at various growth stages

Growth stage	*Intercept, slope and coefficient of determination (r^2)*					
	Erectophile canopy			*Planophile canopy*		
	NRI	*NDVI*	*MSAVI*	*NRI*	*NDVI*	*MSAVI*
Leaf area index						
V6	0·77, −0·38 0·32	−0·77, 0·38 0·32	0·56, −0·89 0·14	0·55, 0·84 0·85	0·44, 0·16 0·40	−0·53, 4·29 0·68
V9	0·43, 1·54 0·84	−0·30, 3·13 0·94	−0·001, 3·72 0·91	−0·12, 0·44 0·85	−0·79, 4·15 0·93	−0·45, 5·54 0·91
V11/12	1·29, 1·80 0·86	−1·23, 4·90 0·99	−0·17, 4·55 0·98	−0·63, 0·49 0·86	−1·19, 5·25 0·97	0·27, 5·00 0·93
V14/15	1·46, 2·21 0·87	1·57, 5·91 0·99	−0·30, 5·52 0·99	−1·05, 0·56 0·95	−1·17, 5·50 0·93	0·53, 4·89 0·97
R1	1·80, 2·08 0·97	0·08, 4·22 0·83	0·70, 4·60 0·87	−0·70, 0·48 0·67	−2·81, 7·21 0·94	0·82, 4·14 0·83
R2	0·79, 3·15 0·99	−2·63, 7·42 0·91	−1·42, 7·97 0·95	−0·34, 0·38 0·96	−2·91, 7·60 0·95	−1·17, 8·01 0·97
Dry matter, t ha^{-1}						
V6	−0·02, 0·56 0·29	−0·09, 1·00 0·37	0·06, 1·30 0·14	0·15, 0·31 0·11	0·20, 0·71 0·24	−0·06, 2·13 0·24
V9	0·93, 1·34 0·93	0·89, 2·57 0·93	0·32, 3·09 0·92	1·09, 1·37 0·40	−0·11, 3·35 0·55	0·28, 4·20 0·47
V12	1·04, 2·53 0·68	−2·86, 7·30 0·91	−1·24, 6·76 0·98	0·94, 3·30 0·91	−3·75, 9·29 0·93	−1·26, 9·04 0·93
V15	0·37, 5·16 0·78	−6·75, 13·88 0·91	−3·81, 13·08 0·99	1·00, 4·88 0·85	−7·97, 15·88 0·78	−3·11, 14·24 0·88
R1	2·35, 7·52 0·94	−4·3, 15·75 0·86	−1·89, 17·04 0·88	1·87, 6·71 0·91	−15·68, 27·91 0·86	−2·48, 17·60 0·91
R2	1·96, 8·74 0·90	−8·82, 22·29 0·96	−4·94, 23·51 0·95	2·57, 8·04 0·82	−9·94, 24·34 0·86	−4·34, 25·60 0·83
Yield, t ha^{-1}						
V6	−15·61, 23·31 0·57	−7·57, 48·98 0·60	−4·04, 61·6 0·32	−12·87, 20·61 0·45	−2·20, 26·9 0·31	−6·67, 57·69 0·16
V9	−3·01, 12·27 0·94	−7·88, 23·50 0·93	−5·76, 28·16 0·91	−3·76, 13·8 0·97	−11·33, 26·91 0·88	−9·88, 37·55 0·94
V12	−0·52, 10·86 0·95	−13·86, 27·18 0·95	−8·16, 25·54 0·96	−2·07, 12·33 0·98	−18·06, 32·70 0·89	−9·89, 32·95 0·95
V15	−0·51, 10·87 0·95	−13·83, 27·14 0·95	−8·14, 25·50 0·96	−1·68, 11·64 0·99	−21·30, 35·69 0·86	−10·98, 32·72 0·95
R1	0·33, 10·26 0·92	−9·94, 23·08 0·97	−6·21, 24·59 0·96	−2·85, 13·17 0·99	−35·42, 52·47 0·85	−11·19, 34·19 0·96
R2	−0·14, 10·70 0·91	−13·48, 27·46 0·98	−8·51, 28·65 0·97	−2·18, 12·56 0·99	−19·87, 35·63 0·87	−12·37, 38·81 0·95

NRI, nitrogen reflectance index; NDVI, normalised difference vegetation index; MSAVI, modified soil adjusted vegetation index.

0·56 for the NDVI, SAVI, MSAVI and the NRI, respectively. The reason for the lower value of r^2 in the LAI–NRI relationship was possibly due to the soil background effect. At the V6 growth stage, the greatest value for r^2 (0·69) was produced by the NRI followed by the MSAVI (0·60), SAVI (0·57) and the NDVI (0·56). Considering that the value of r^2 for the NRI was lower than those for the NDVI, SAVI and the MSAVI at the V9 growth stage, the value of r^2 for the NRI at the V6 growth stage seems to be very high. This may be a result of random sampling error or a positive effect of the normalisation at each growth stage because normalisation using a reference plot in the NRI enables researchers and other users to make site and weather dependent calibrations. This could be considerably important since the potential growth may differ locally and temporally. The performance of the NRI improved gradually over the growing season with a drop at the R1 growth stage. The drop at the R1 growth stage might be due to the pollen cover on the canopy observed during the phenological observations. The NDVI and MSAVI had a similar performance drop in estimating the LAI.

Table 3
Values of the canopy cover with respect to the applied nitrogen levels for both canopy types at various growth stages

Nitrogen level, kg ha^{-1}	*Canopy cover, %*					
	Growth stages					
Pioneer	*V6*	*V9*	*V12*	*V15*	*R1*	*R2*
0	0·22	0·44	0·53	0·67	0·75	0·69
56	0·30	0·56	0·69	0·82	0·78	0·74
224	0·32	0·64	0·84	0·89	0·90	0·87
112	0·30	0·68	0·75	0·78	0·87	0·87
184	0·34	0·68	0·77	0·86	0·88	0·81
168	0·23	0·83	0·88	0·91	0·93	0·91
NC+1598						
0	0·19	0·36	0·43	0·48	0·50	0·61
56	0·23	0·52	0·64	0·72	0·75	0·69
224	0·34	0·60	0·83	0·86	0·92	0·88
112	0·30	0·64	0·83	0·76	0·81	0·86
184	0·32	0·69	0·64	0·85	0·85	0·80
168	0·30	0·65	0·77	0·87	0·92	0·91

Table 4
The values for the coefficient of determination r^2 for the relationships between the vegetation indices and leaf area index (LAI) of the two maize hybrids at various growth stages

Growth stage	*Coefficient of determination (r^2)*			
	NRI	*NDVI*	*SAVI*	*MSAVI*
V6	0·69	0·56	0·57	0·60
V9	0·56	0·87	0·63	0·85
V12	0·80	0·85	0·81	0·49
V15	0·87	0·97	0·97	0·75
R1	0·71	0·56	0·84	0·60
R2	0·92	0·91	0·90	0·91

NRI, nitrogen reflectance index; NDVI, normalised difference vegetation index; SAVI, soil adjusted vegetation index; MSAVI, modified soil adjusted vegetation index.

Results indicated that all indices had merit in estimating the LAI efficiently at various growth stages.

The vegetation indices were also correlated with dry matter at each growth stage. As seen in Table 5, the relationships were strong at all growth stages except at the V6 and V9 growth stages. Data indicated that the NRI was a comparable index with the NDVI, SAVI and the MSAVI in estimating dry matter production of maize. Its performance seemed to be growth-stage dependent. The SAVI produced a similar trend over the growing season; however, it related better than the NRI with dry matter at the V6 growth stage. The value of r^2 for the MSAVI at the V6 growth stage was 0·64 which was better than that of the SAVI (0·33).

Grain yield was well correlated with the vegetation indices at all stages except at the V6 growth stage

Table 5
The values for the coefficient of determination r^2 for the relationships between the vegetation indices and dry matter of the two maize hybrids at various growth stages

Growth stage	*Coefficient of determination (r^2)*			
	NRI	*NDVI*	*SAVI*	*MSAVI*
V6	0·02	0·25	0·33	0·64
V9	0·30	0·61	0·36	0·58
V12	0·69	0·90	0·88	0·88
V15	0·80	0·86	0·87	0·61
R1	0·82	0·61	0·89	0·66
R2	0·87	0·89	0·73	0·89

NRI, nitrogen reflectance index; NDVI, normalised difference vegetation index; SAVI, soil adjusted vegetation index; MSAVI, modified soil adjusted vegetation index.

Table 6
The values for the coefficient of determination r^2 for the relationships between the vegetation indices and grain yield of the two maize hybrids at various growth stages

Growth stage	*Coefficient of determination (r^2)*			
	NRI	*NDVI*	*SAVI*	*MSAVI*
V6	0·48	0·30	0·10	0·22
V9	0·94	0·85	0·90	0·86
V12	0·95	0·91	0·75	0·92
V15	0·96	0·88	0·85	0·89
R1	0·90	0·70	0·93	0·78
R2	0·93	0·91	0·85	0·89

NRI, nitrogen reflectance index; NDVI, normalised difference vegetation index; SAVI, soil adjusted vegetation index; MSAVI, modified soil adjusted vegetation index.

(Table 6). At this growth stage, the NRI followed by the NDVI had higher values of r^2 while the SAVI produced the lowest values of r^2. Later in the growing season all the vegetation indices seemed to be very effective in predicting maize yield. The NRI showed considerable consistency for correlating with the grain yield of maize; values for r^2 were over 0·90 except at the V6 growth stage.

Figures 5–7 show the LAI, dry matter, and grain yield maps generated from the measurements made in the verification study and from estimates by the relationships developed. LAI, dry matter and yield maps represent the V9 growth stage. Zonal statistical analysis was conducted to obtain statistics in terms of the mean and coefficient of variation for individual plots; these are summarised in Table 7.

Figure 5 shows the LAI maps from measurements and the estimates. There are some similarities between the maps generated from the equations and the one

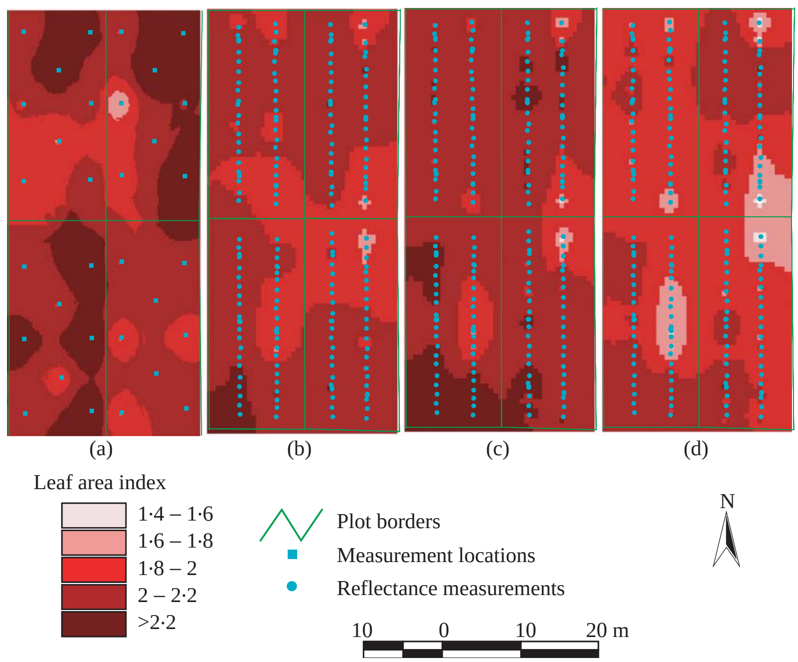

Fig. 5. Leaf area index (LAI) maps for a planophile-canopy-type hybrid at the V9 growth stage: (a) as measured; (b) estimated by nitrogen reflectance index (NRI); (c) estimated by normalised difference vegetation index (NDVI); and (d) estimated by modified soil adjusted vegetation index (MSAVI)

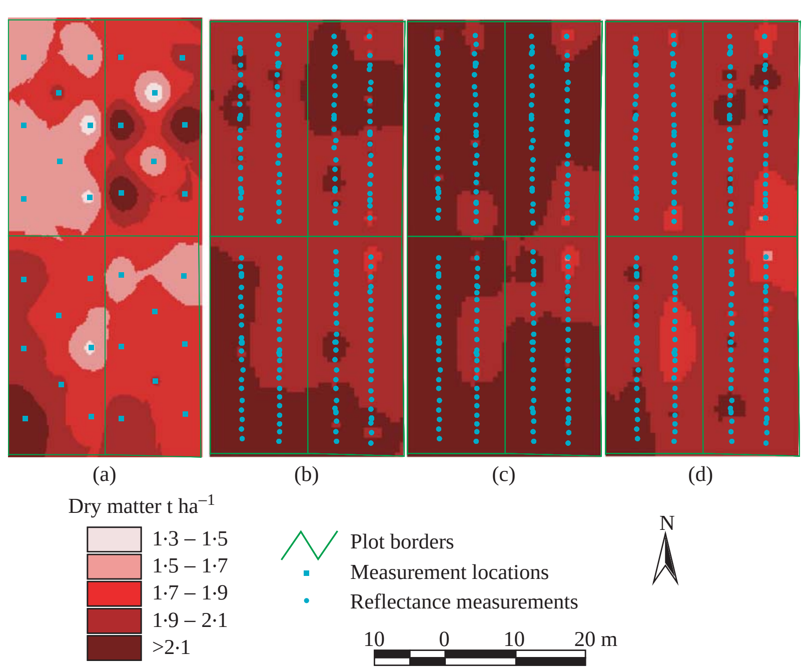

Fig. 6. Dry matter (t ha^{-1}) maps for a planophile-canopy-type hybrid at the V9 growth stage: (a) as measured; (b) estimated by nitrogen reflectance index (NRI); (c) estimated by normalised difference vegetation index (NDVI); and (d) estimated by modified soil adjusted vegetation index (MSAVI)

generated from measurements. Large areas visually showed disagreement between the estimates and measurements for the verification study. However, data analysis indicated that more than 90% of the LAI values estimated by vegetation indices were in the 95% confidence limits of the regression equations. The

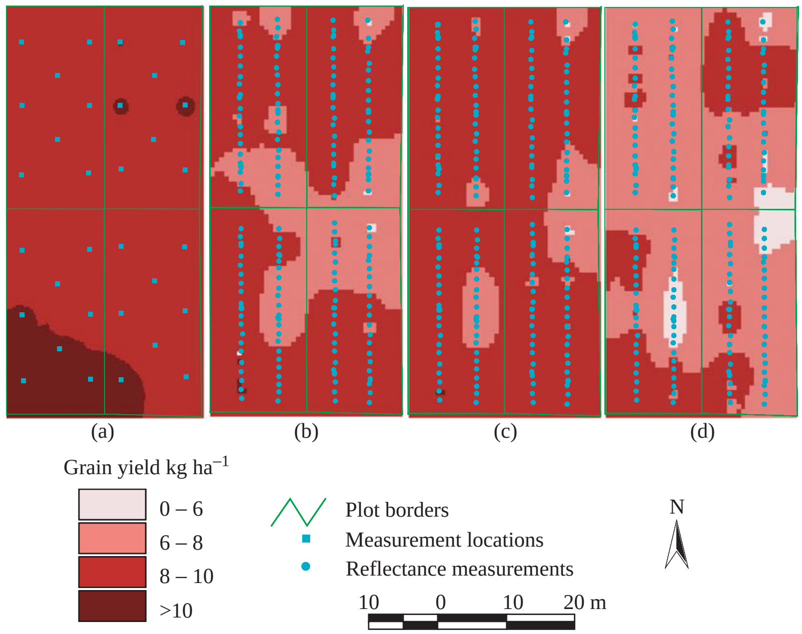

Fig. 7. Grain yield (kg ha^{-1}) maps for a planophile-canopy-type hybrid at the V9 growth stage: (a) as measured; (b) estimated by nitrogen reflectance index (NRI); (c) estimated by normalized difference vegetation index (NDVI); and (d) estimated by modified soil adjusted vegetation index (MSAVI)

Table 7

Mean and coefficient of variation (CV) of leaf area index (LAI), dry matter, and yield as measured and calculated from nitrogen reflectance index (NRI), normalized difference vegetation index (NDVI) and modified soil adjusted vegetation index (MSAVI) for individual plots

Plot no	*Measured*		*Estimated from NRI*		*Estimated from NDVI*		*Estimated from MSAVI*	
	Mean	*CV*	*Mean*	*CV*	*Mean*	*CV*	*Mean*	*CV*
Leaf area index								
6	2·20	0·10	2·02	0·02	2·10	0·02	1·92	0·03
7	2·07	0·07	2·02	0·04	2·09	0·05	1·94	0·07
14	2·07	0·05	2·28	0·05	2·14	0·05	1·96	0·06
15	2·21	0·05	2·01	0·04	2·09	0·04	1·92	0·06
Dry matter, t ha^{-1}								
6	1·89	0·08	2·06	0·01	2·15	0·02	1·99	0·02
7	1·68	0·05	2·07	0·03	2·13	0·04	2·00	0·05
14	1·80	0·05	2·11	0·03	2·18	0·05	2·01	0·05
15	1·88	0·09	2·05	0·03	2·13	0·04	1·98	0·04
Yield, t ha^{-1}								
6	9·25	0·04	8·17	0·04	8·60	0·03	7·32	0·06
7	9·30	0·03	8·19	0·09	8·51	0·08	7·45	0·13
14	9·43	0·05	8·67	0·09	8·84	0·08	7·62	0·11
15	9·89	0·04	8·08	0·09	8·50	0·07	7·28	0·11

map generated from the NRI had slightly larger areas of high LAI; however, the zonal statistics (Table 7) indicated that the largest difference between the measured and calculated maps was about 10% for all the NRI and NDVI. The MSAVI underestimated the LAI by about 13% in plots 6 and 15. The LAI values in Table 7 are similar to the findings of Walburg *et al.* (1982).

Dry matter was overestimated by the vegetation indices (*Fig. 6*). The MSAVI and NRI produced slightly better dry matter means than the NDVI. The largest dry matter was measured in plot 6 with a value of 1·89. This value is lower than that given by Walburg *et al.* (1982). This result suggests that there could have been some errors in our measurements or the differences between the total areas of the remotely sensed data and ground measurement were relatively high. The area for ground sampling for the verification study was $0{\cdot}34\,m^2$ while the area covered by the radiometer was $5{\cdot}3\,m^2$.

As shown in the maps of *Fig. 7* and the data of Table 7, the estimates of all three indices were considerably lower than the measured grain yield. None of the three gave an accurate yield estimate. The yield estimates of the MSAVI were lower than those by the NRI and NDVI. However, the MSAVI estimates of yield were better spatially than those by other vegetation indices. The reason for lower estimates of the MSAVI could be due to the very steep slopes that were observed in the relationships between the indices and dry matter and grain yield. The yield estimates of the MSAVI were lower than the measured yield by about 21%. On the other hand, the NRI produced yield estimates on the average 13% lower than the measured ones. The corresponding value for the NDVI was only 9%. The maps generated from the NRI and NDVI were similar to each other showing similar variability in the field while less variability was observed in the map generated from measurements. The discrepancies that exist between the estimated and measured grain yield maps could be due to fewer measurement points in the verification study as compared to the fertiliser level study from which the relationships were developed.

4. Conclusions

Data supported that there was a near-linear relationship between the normalised difference vegetation index (NDVI) and the leaf area index (LAI). However, the linear relationship could be safely used for practical purposes. The nitrogen reflectance index (NRI) and the NDVI seemed to depend on crop canopy type, while the modified soil adjusted vegetation index (MSAVI) appeared to be neutral with regard to canopy types. Examining the relationship between the vegetation indices and the LAI, as well as dry matter, the MSAVI did not seem to be superior to the NDVI; however, the MSAVI produced a spatially comparable map of yield estimates while underestimating the yield.

The results indicated that the NRI could successfully be used in estimating plant growth parameters. The NRI correlated to grain yield relatively better than both the MSAVI and NDVI; this is probably because it is normalised with a reference. The growth-stage dependence of the NRI could be an advantage for precision farming applications, because some degree of smoothing would occur in the relationships developed for the whole growing season. Further research is required to verify the usefulness of the NRI in estimating plant growth parameters.

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